Appendix A

Advances in Integrated and Issue-Specific Modeling

A successful assessment relies on modeling. Issue-specific models are used to understand such processes as pollution transport and diffusion or visibility impairment and, in some cases, to make predictions. In performing an integrated assessment of a science-policy issue that involves many disciplines, analysts must be able to understand and assess the relationships and dependencies between the disciplines. Integrated models that link issue-specific models are tools that scientists and economists can use to provide the understanding necessary for an integrated assessment. This appendix provides descriptions of a few issue-specific and integrated models that are relevant to the acid deposition issue.

Integrated Models

Integrated models link issue-specific models to enhance understanding of a complex issue that is broad in scope. This section describes three integrated models of the acid deposition issue. They all include emissions, transport and diffusion, deposition, and economics in their frameworks but have different modeling approaches that match the needs of their users. The Tracking and Analysis Framework was developed in the United States, while RAINS and RAISON were developed by the European Community and Canada, respectively.

Tracking and Analysis Framework

With the passage of the 1990 Clean Air Act Amendments, the United States embarked on an acid deposition control policy that has been estimated to cost billions of dollars. The Amendments created a major innovation in environmental regulation by introducing market-based incentives—specifically, trading among electric utility companies in allowances to emit sulfur dioxide. NAPAP is charged with (1) evaluating the status of the implementation, effectiveness, and costs and benefits of the acid deposition control program created by Title IV of this Act, and (2) determining whether additional reductions in deposition rates are necessary to prevent adverse ecological effects.

To help NAPAP face this challenge, the U.S. Department of Energy, with support from other federal agencies, sponsored the development of an integrated assessment model, known as the Tracking and Analysis Framework (TAF). TAF was developed in less than two years with relatively modest resources for such a comprehensive model. This rate of progress was made possible by an innovative combination of methods for integrated assessment. An overview of TAF follows with an outline of these methods, including references to companion documents that provide more details on selected methods and modules.

General Objectives

Following are the general objectives of TAF.

A framework for integrated assessment: TAF is designed to provide a comprehensive framework to address the major issues of concern, from end to end—that is, from the effects of the Clean Air Act Amendments on reducing emissions of pollutants, atmospheric transport, deposition, and environmental degradation, all the way to economic valuation of the environmental benefits of emission reductions. A variety of modules can be slotted into this framework. At present, the areas of environmental effects addressed by TAF include visibility, aquatic ecosystems, soils, and human health. Modules for forests and terrestrial ecosystems, crops, and materials remain to be added.

Complete integration: TAF is designed to include all components within a unified computing environment so that they can be examined and evaluated together, including exploration of the interactions among components.

Agility and flexibility: TAF is designed to be run on a personal computer in a few minutes, and to allow easy modification of input assumptions and reconfiguration to assess alternative policy scenarios, as new policy issues arise and new data and science become available. It is designed to allow analysts to address new questions in hours or days, rather than the weeks or months many models need.

Transparency: TAF is designed to provide the models in a form whose structure, relationships, and assumptions can easily be inspected and reviewed. It is designed as a "glass box," rather than a "black box," model.

Scientific credibility: TAF is based on the best available peer-reviewed science and data.

Explicit treatment of uncertainty: TAF provides explicit representation of the uncertainties due to limitations in scientific understanding, lack of data, and model precision.

Modeling Methods

The following set of methods was adopted to achieve these general objectives:

Influence diagrams: Influence diagrams provide a graphical representation for display of the qualitative structure of models.

Modular structure: The model is organized throughout in a hierarchy of modules so that each module is simple enough to be easily understood.

Integrated documentation: Documentation is integrated, explaining the variables and their role in the computer representation.

Reduced-form models: Most modules are "reduced-form" models—that is, simplified models fitted to more detailed, scientific full-form models. They derive their scientific credibility from the quality of their fit to the detailed models. Both the full-form and the reduced-form models used in TAF are peer reviewed.

Probabilistic analysis of uncertainty: Probability distributions are used to represent variability, uncertainty due to lack of scientific knowledge or data, and imprecision due to model approximations. Monte Carlo and related methods are used to propagate and combine these distributions to assess the implied uncertainty in the results, and to compare the importance of the various sources of uncertainty.

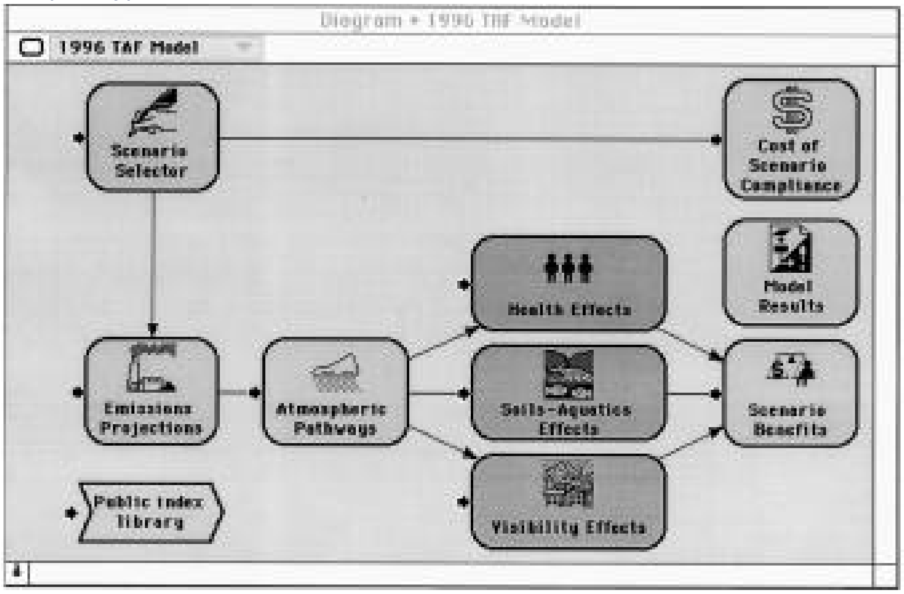
Progressive refinement: The team has developed TAF as a series of prototypes of increasing sophistication and refinement, progressively reviewing and refining each to create the next version. Several of these methods have been used in the development of other integrated assessment models. In adopting and refining the entire set of methods, the team found significant synergies among them, leading to what is believed to comprise some important innovations in integrated assessment methodology. The use of many of these methods has been facilitated by the use of Lumina's Analytica, which is software for quantitative modeling and integrated assessment. Analytica (Henrion et al., 1996) provides a variety of features used in TAF, including influence diagrams, hierarchies of modules, integrated documentation, and Monte Carlo simulation.

Overview of TAF Modules

A comprehensive assessment of the costs, benefits, and effectiveness of Title IV of the Clean Air Act Amendments requires consideration of many issues. Figure A-1 shows the top level of TAF as an influence diagram. Each of the nodes on the diagram represents a module currently in TAF.

The scenario selector on the top left allows the model user to select one or more scenarios for projecting future emissions and to assess and compare the effects of those emissions. Users can specify their own scenarios, making assumptions about future growth rates in emissions, by pollutant type (SO_X and NO_X), and source region. Alternatively, users can select a predefined scenario from recent U.S. Environmental Protection Agency (EPA) projections, or estimated projections from one of 16 scenarios defined by TAF's emissions module. These 16 scenarios are based on

Figure A-1. A computer screen image shows a top-level influence diagram from the TAF prototype.



combinations of Phase I caps only and Phase II caps, with and without trading in emission allowances, and with alternative assumptions about future electricity demand growth rates and power plant retirement ages.

TAF currently contains 10 modules developed by over 30 people at 10 different sites, including four consulting firms, three national laboratories, two universities, and a nonprofit foundation.

Model Transparency and Organization

A common complaint about computer models—be they scientific or policy models—is that they are too complicated and too poorly documented to be understood, verified, or trusted. Typically, model documentation is created and updated separately from the computer model, with the result being inconsistent with the model it is supposed to document. In some cases, models are proprietary, and their developer wishes to keep their internal structure secret. Since a major objective of TAF is to support communication and coordination among scientists and policy analysts, an essential requirement for TAF is that the models be documented clearly and consistently.

The Module Hierarchy

TAF employs features of Analytica to display the model as a hierarchy of influence diagrams and to integrate model documentation in the same computer representation used for computation. Figure A-1 shows the top-level influence diagram, including the key modules and arrows indicating the dependencies among these modules.

Each module consists of a diagram, showing the key inputs and outputs, and submodules containing the details of the model. These submodules are themselves arranged hierarchically, as illustrated in Figure A-2. Clicking the mouse on one of these nodes in the diagram opens up the diagram for the model it contains. This model hierarchy in TAF extends down to six levels in parts of TAF.

Each variable in a model is represented in a diagram by a node with a thin outline. Variables that are defined as uncertain, using a probability distribution are represented by oval nodes. Other variables are represented as rounded rectangles. Index variables are represented by parallelogram nodes.

Integrated Documentation

Each variable in TAF is documented by a card (object window), containing a set of attributes describing the variable, as illustrated in Figure A-3. The card shows the variable class, name, units of measurement, description, definition (mathematical relationship for calculation), list of inputs and outputs, and, optionally, a reference to the publication or authority on which the definition is based. When the definition of a variable is specified or modified, Analytica automatically updates the lists of inputs and outputs and the arrows in the parent diagram to reflect any changes in the dependency relationships.

Scientific Credibility and Reduced-Form Models

Previous attempts to develop integrated assessment models have sometimes been criticized as lacking sound scientific foundations due to the degree of simplification (Balson and North, 1982; Alcamo et al., 1987). The challenge is to reconcile the need for integrated assessment models to be based on the best

Figure A-2. This example of the module hierarchy in TAF shows that double clicking the mouse on a module node (thick outline) opens up the diagram for that module.

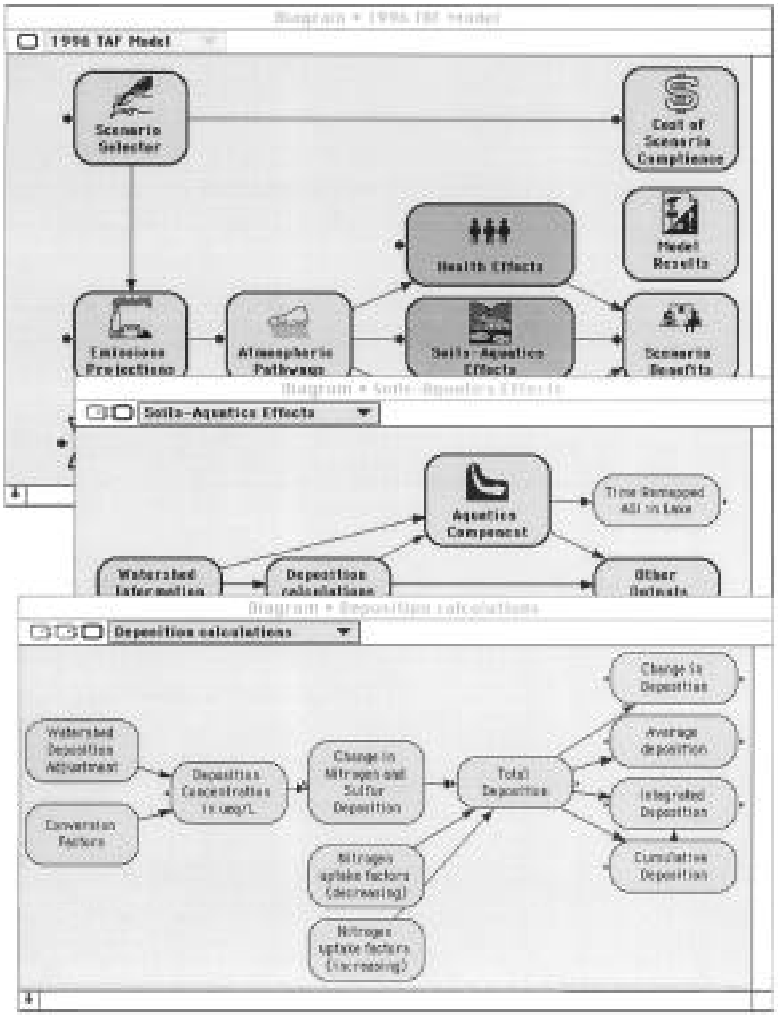
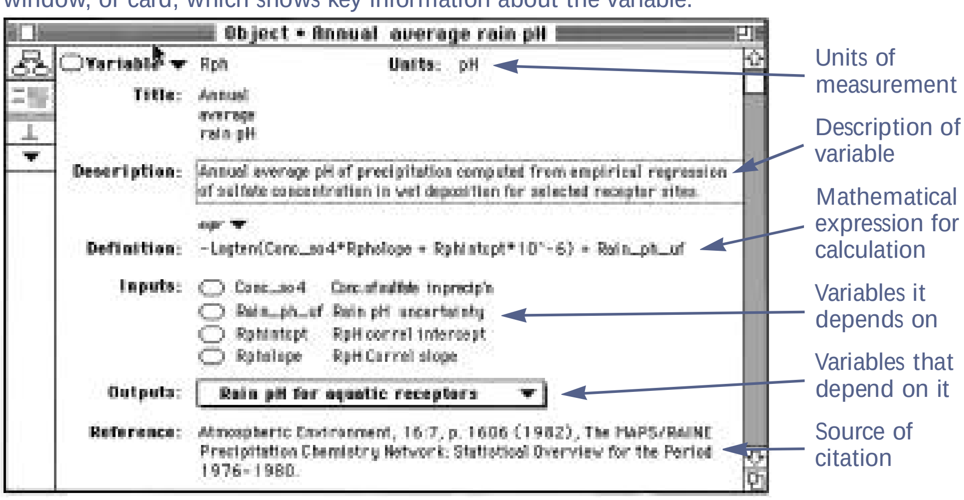


Figure A-3. Each variable is documented internally with an object window, or card, which shows key information about the variable.

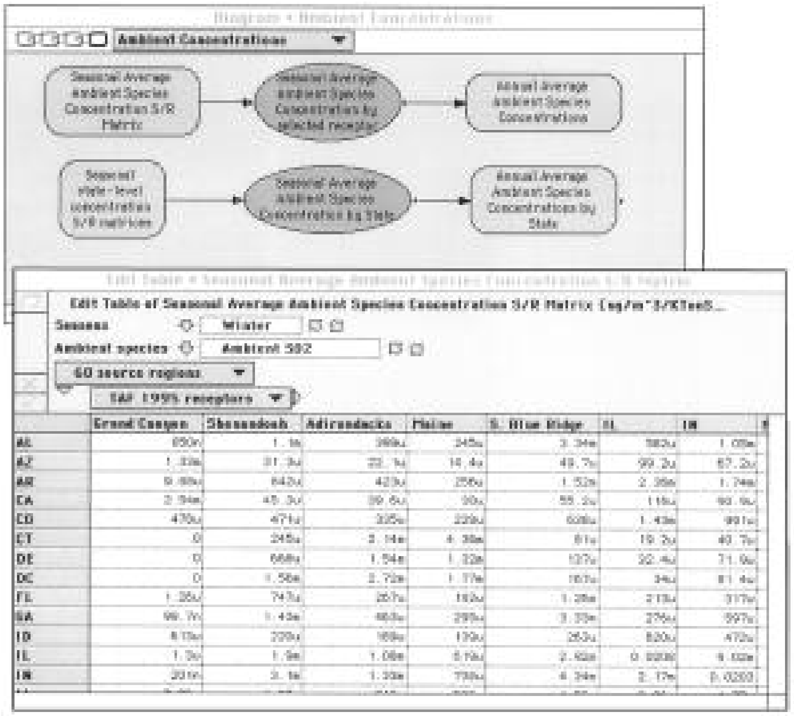


available scientific data and models yet be small, agile, flexible, and comprehensible. TAF meets this challenge by building most modules as reduced-form models based directly on the best available detailed scientific model or data.

Reduced-form models are simplified models, intended to approximate the behavior of larger, more complicated full-form models or data sets. Reduced-form models contain fewer variables, less causal detail, or higher levels of aggregation. Their performance is calibrated against or fitted to the performance of the full-form, detailed models. In practice, the approximation uncertainty introduced by the simplification for the reduced-form models in TAF is usually dwarfed by the inherent uncertainty in the full-form model. In these cases, the loss in precision from the reduced-form model is negligible.

In integrated assessments, it is generally necessary to link several models together—the outputs of one are matched to the inputs of the next. Typically, problems arise because the detailed models are at different levels of aggregation. For example, emission projections may be by season for each power plant, but the atmospheric transport model may need emissions on a daily basis aggregated by a 20-kilometer grid square. Also, the file formats and platforms are often incompatible. Moreover, the models are so large that it is too expensive and time consuming to run them for many different scenarios, especially to handle uncertainty using Monte Carlo or other techniques. It is often impractical to reconfigure and rerun them every time a new policy problem arises. Reduced-form models can obviate these problems, provided they are designed explicitly to use compatible levels of aggregation and file formats.

Figure A-4. The lower window shows part of the normalized transport matrix by source plant and receptor region, as a detail of the diagram in the upper window. The two-dimensional transport matrix displayed is for winter and ambient SO_2, and is a slice from a four-dimensional array, indexed by four seasons and ambient species.



Reduced-form models may be developed or formulated in a wide variety of ways. Following is a description of the approach employed for the atmospheric transport module.

Reduced-Form Models for the Atmospheric Transport Module

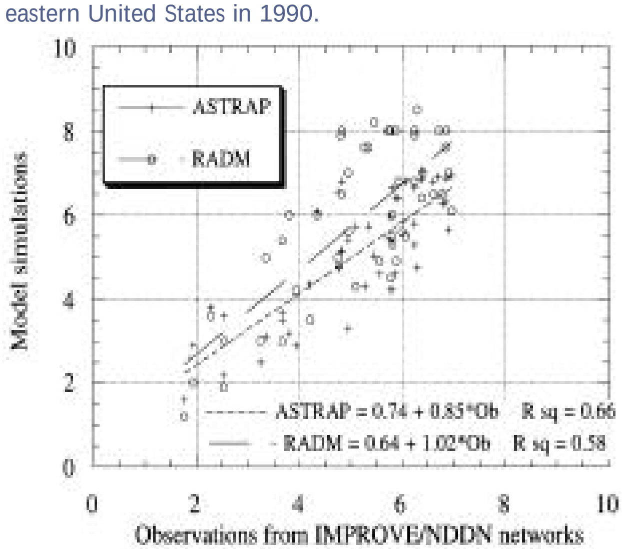
The atmospheric pathways module of TAF is a reduced-form model based on results from the Advanced Statistical Trajectory Regional Air Pollution (ASTRAP) model, a detailed long-range atmospheric transport model developed at Argonne National Laboratory (Shannon, 1981). The reduced-form models consist of source–receptor matrices, normalized to unit emissions at each source. The normalization allows the model to be applied to any emission scenario. Since ASTRAP generates ambient concentrations and deposition rates that are linear in emission rates, this normalization involves no additional approximation.

The 60 sources are centroids of the United States, Canadian provinces, and northern Mexico. Temporal aggregation is by season and year. Transport matrices are provided for dry and wet deposition for SO_X and NO_X.

Specific receptors have been selected for the visibility, aquatics, crops, and human health effects. Figure A-4 shows the top left corner of a source–receptor matrix for ambient SO_2 in winter.

Shannon et al. (1997) have compared the performance of ASTRAP with a nonlinear transport model called RADM (Regional Acid Deposition Model), and actual observations for annual average atmospheric concentrations at selected receptor sites in the eastern United States. Figure A-5 shows an example comparison with regression lines fitting the observations to predictions for each model. Both models appear to underestimate the observations on average. Both models show a similar quality of fit to the data. Since ASTRAP is a linear model, it generates ambient concentrations and deposition at each receptor that are proportional to the emissions at the sources. Therefore, representing it by normalized transport matrices, as in TAF, introduces no additional approximation imprecision for a given time period (seasons). In other words, there is no approximation uncertainty introduced by the reduced-form model beyond the uncertainty inherent in the detailed model on which it is based. Moreover, the uncertainty of the latter appears to be no more at the selected levels of aggrega-

Figure A-5. A comparison of predictions by ASTRAP (the TAF module) and RADM (another more detailed transport model) with actual observations of annual average concentrations of atmospheric sulfate (µg/m³) in the eastern United States in 1990.



tion over space and time than RADM, which is significantly more complex than ASTRAP.

Progressive Refinement

Model development is—or should be—a learning process. It requires many decisions about the level of detail and aggregation of each variable, making compromises between accuracy and practicality, between detail and computer time and memory, between the policy questions of concern and the pragmatic limitations on what questions the model can address. Finding the best trade-offs is a major challenge, even for the most experienced modelers. The most satisfactory results are obtained when the modelers can revisit decisions in the light of experience with early versions of the model—expanding, simplifying, and refocusing models as the process continues. This process is called progressive refinement.

Progressive refinement was adopted as the approach to TAF from the start, beginning with an earlier model named ADAM, developed for NAPAP in the mid-1980s at Carnegie Mellon University. In 1993, NAPAP commissioned a revised prototype integrated assessment model, based on ADAM, which came to be known as TAF. And so began the multiple cycles of progressive refinement, which were essential in obtaining a fully integrated model.

TAF Peer Review

An intensive peer review of TAF by 12 scientists in December 1995 concluded that TAF was generally successful in meeting its objectives (Report on the Peer Review, 1996). The development team provided considerable refinement in the following year to address remaining concerns and to improve the analysis.

Hierarchical influence diagrams have proved valuable as a visual tool to support transparency for organizing and communicating complex models. Analytica's tools for integrated documentation and array abstraction have also proved helpful. Members of the TAF team and reviewers have been able to scrutinize model structure and assumptions using the built-in model diagrams and documentation.

TAF is small enough to run in a few minutes, allowing multiple Monte Carlo runs for comprehensive uncertainty analysis. It is also flexible enough to be rapidly reconfigured to address new policy issues. Yet it is derived from credible, detailed scientific models. The key to reconciling these apparently conflicting goals has been the development of reduced-form models for key modules. Thus, the relatively small size and simplicity of TAF impose no important loss of precision in the results that it generates.

The general approach has been one of progressive refinement, in which each module and the integrated model are developed as a series of versions, starting with module specifications, being progressively refined in response to review and critique by other members of the team. The current version of TAF is the result of four major cycles of refinement, each comprised of a number of minor cycles.

The methods and tools that have been developed and the experience gained in developing TAF could be of value to other teams involved in the collaborative development of models for integrated assessment. Other domains of application might include integrated assessments for regional or local air pollution policy, and for international environmental problems, especially for global climate change.

Exercises with Historical Data and the Aquatics Module

In this section, the transport and aquatics modules in TAF are exercised using historical emissions data from the period 1980 through 1995. Some of the intermediate ambient concentration and deposition results are presented, and the aquatics module is used to estimate the changes in alkalinity for a series of lakes in the Adirondack Mountain region of New York. The acid stress index for three fish species within these lakes is also estimated. Finally, some of the sensitivity and uncertainty analyses made possible using the TAF framework are presented.

Historical Emission Trajectories

The utility SO_X and NO_X emission trajectories used in this exercise are derived from the EPA's emission databases (see footnote 1). Additional nonutility emissions (from commercial, industrial, and transportation sources) are from the emission databases at Argonne National Laboratory (see footnote 2). Mexican and

[1] *Acid Rain Division, Environmental Protection Agency, Washington, DC.*
[2] *Environmental Research Division, Argonne National Laboratory, Argonne, IL.*

Figure A-6. National SO_X and NO_X emissions.

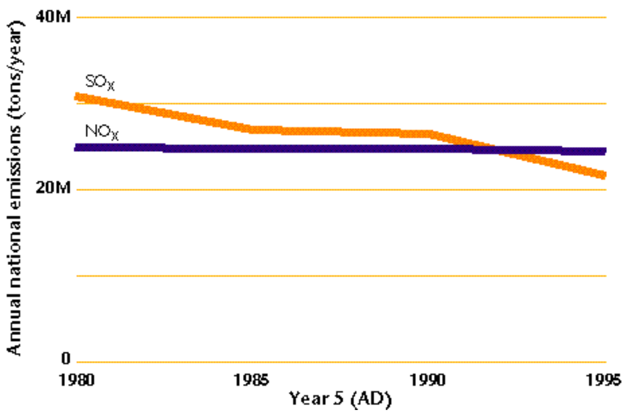
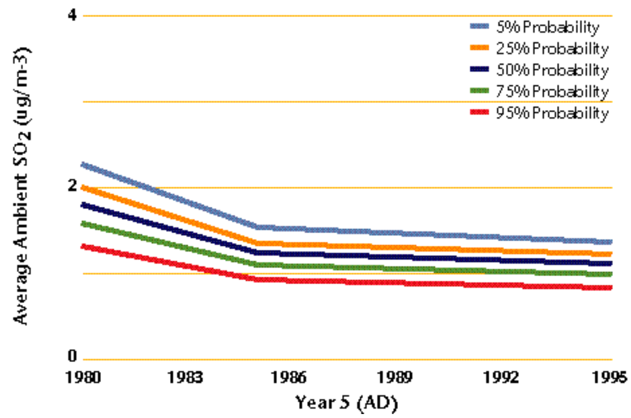


Figure A-7. Annual average species concentration of SO_2 in the Grand Canyon area.



Canadian emission trajectories are also included because of their contributions to ambient pollutant concentrations within U.S. borders.

The emissions are aggregated to the state level in TAF. Figure A-6 includes utility and nonutility sources of U.S. emissions during 1980-1995.

TAF also contains emission projections based on models run by ICF for EPA and models run by Argonne National Laboratory for the Department of Energy. Other emission projections can be input by TAF users, and propagated through the entire model.

Estimating Ambient Concentrations and Deposition in the Pathways Module

The pathways module uses linear source–receptor matrices to calculate seasonal ambient pollutant concentrations and deposition estimates integrated over states and at a few selected point receptors, based on state-level data from the emissions module. Because the TAF module is primarily concerned with annual averages of deposition and ambient pollutant concentration levels (a few exceptions are handled downstream in the assessment), a linear approximation of transport processes is appropriate.

The source–receptor matrices are from the ASTRAP model. Using historical emissions data, the ASTRAP matrices have been validated against ambient concentration/deposition data. Eleven years of wind and precipitation data have been used in the model to estimate the variability of model results based on climatological variability. The resulting variability in ambient concentration and deposition estimates was then incorporated into the module to represent climatological variability. Normal distributions representing the annual variability of the source–receptor relationship are multiplied by the concentrations and depositions estimated at each receptor site.

The variability in ambient concentrations based on climatic fluctuations is illustrated in Figure A-7, for micrograms per cubic meter of SO_2 in the Grand Canyon area. Probabilities of occurrence of 5%, 25%, 50% (median), 75%, and 95% are used to represent the annual variability of average ambient pollutant concentration.

This variability is significant when examining the baseline or Title IV pollutant concentrations alone, but when the Title IV concentrations are subtracted from the baseline concentrations to obtain an estimate of concentration reductions under Title IV, much of the year-to-year variability due to climatological differences is canceled out, resulting in estimates of reduced ambient concentrations. The climatological variability factored into the transport of pollutants has a measurable effect on reductions in pollutant concentrations, as demonstrated by the confidence interval surrounding the mean estimate of ambient pollutant concentrations. The next section compares this variability to other sources of variability and uncertainty that contribute to the aquatic effects of acid deposition.

Aquatics Effects: Using TAF to Rank Effects

The aquatics module is a reduced-form version of the Model of Acidification of Groundwater in Catchments (MAGIC). Using deposition data from the pathways module and Adirondack lake background data, the aquatics module calculates lake pH, acid-neutralizing capacity, base saturation, fish species richness, and fish acid stress indices for 33 Adirondack lakes. The module has been calibrated to data and results from the full-form version of MAGIC, and performs comparably, despite its much more modest computational requirements.

This discussion is limited to the acid stress index, also known as the conditional mortality rate. The acid stress index is a common estimate of the increased likelihood that a fish of a given life stage will die when exposed to the specified water quality conditions, over and above the mortality expected in a circumneutral reference water. Higher numbers indicate higher stress and increased likelihood of death. The benefits module in TAF uses the acid stress index computed at the Adirondack lake sites, for three fish species, to estimate the catch per unit of effort expended by recreational fishermen. Figure A-8 contains the median (50%) brook trout acid stress index results for a single Adirondack lake. Figure A-8 also shows 25% and 75% probability estimates. The confidence intervals are not symmetric, indicating that the distribution of possible acid stress index values is itself asymmetric, with a right-hand tail.

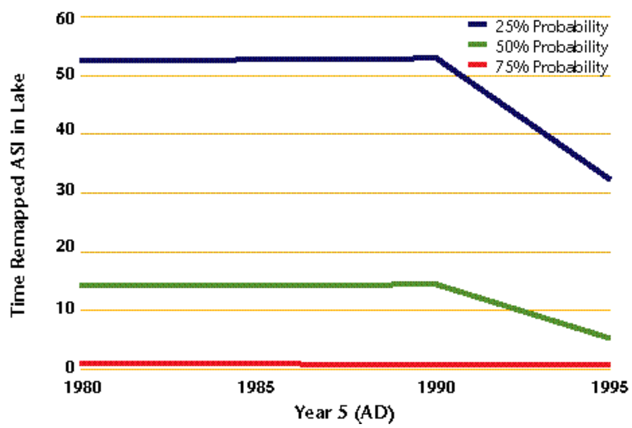
Aquatics Effects: Using TAF to Rank Sensitivities and Uncertainties

The uncertainty around the acid stress index includes a fraction above zero. This indicates that, when the uncertainty in the aquatics modeling and natural climatological variability is taken into account, a reduction in the acid stress index cannot be guaranteed. That said, the chance of a nonzero, favorable change in acid stress index (i.e., a reduction) is quite large. An importance analysis can be used to compare the relative contributions of the uncertainties in the model to the acid stress index results. The uncertainties affecting the acid stress index include:

Uncertainty in deposition from the pathways module. This is similar to the climatological variability in the visibility module, except it is expressed as cumulative acid deposition instead of annual ambient concentration.

Uncertainties in the fit between MAGIC and empirical data. There are four components to this uncertainty: uncertainty in the estimation of lake calcium concentrations, uncertainty in the estimation of acid-neutralizing capacity, uncertainty in the estimation of lake pH from acid-neutralizing capacity, and uncertainty in the estimation of acid stress index from lake pH (described with four parameters).

Figure A-8. Acid Stress Index and confidence intervals for an Adirondack lake.

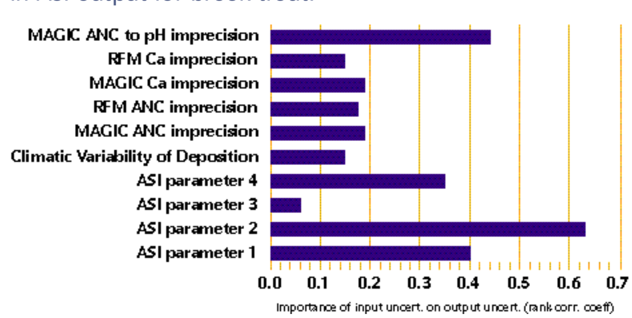


Uncertainties in the fit between the reduced-form model version in TAF and the full-form MAGIC. There are two components to this uncertainty: (1) uncertainty in the estimation of lake calcium concentrations and (2) uncertainty in the estimation of lake acid-neutralizing capacity.

The reduced-form model and MAGIC uncertainties were quantified from the results of linear and nonlinear regressions. Climatic variability was quantified by measuring variability in ASTRAP deposition results using historical wind trajectory data from 11 separate years. These sources of uncertainty are ranked using an importance analysis. The results of the analysis are shown in Figure A-9.

The uncertainty in the relationship that translates pH to acid stress index (ASI parameters 1, 2, and 4) dominates the result. The conversion from acid-neutralizing capacity (ANC) to pH also provides a significant amount of uncertainty in the result. These uncertainties swamp the other sources of uncertainty in the model, including the imprecision in the reduced-form

Figure A-9. Importance of uncertain inputs on uncertainty in ASI output for brook trout.



model (RFM) and the variability caused by year-to-year changes in deposition. Because the overarching uncertainties in MAGIC dominate the uncertainty in the result, we conclude that the reduced-form version of MAGIC within TAF performs comparably to MAGIC.

Note also that the climatological variability is not large compared to some of the other uncertainties. This is true in part because much of the climatological uncertainty is canceled out when the difference of the baseline and comparison scenario results is taken. The climatological uncertainty is the same across the two scenarios, so it is reduced when the difference of the two scenarios is taken.

This analysis identifies the conversion of pH to acid stress index and of acid-neutralizing capacity to pH as critical sources of uncertainty in the aquatics module. Acid-neutralizing capacity is converted to pH by using a four-parameter nonlinear equation based on work by Small and Sutton (1986), calibrated to data for the 33 Adirondack lakes considered in TAF. Whether this source of uncertainty should be refined and reduced in future versions of the aquatics module depends on the effect of this uncertainty in calculation of aquatics benefits.

Future TAF Analyses

The analyses described here are just a small sample of the potential of an integrated assessment. Future analyses in TAF can compare results not only across effect modules, but also across unmodeled effects using back-of-the envelope scoping analyses. These analyses will permit prioritization of additional modules to be added to TAF.

As additional information on the costs of Title IV regulations on utilities is integrated, utility costs can be compared to the benefits calculated in TAF to determine whether the subset of benefits calculated is sufficient to suggest that Title IV is cost-effective. Also, the capability exists to compare the geographic distribution of costs with the distribution of benefits, because TAF calculates both costs and benefits on a state level.

The model is able to compare both uncertainties that propagate through several modules, and uncertainties across different effects and benefits. It enables comprehensive identification of those inputs and model forms sensitive to change and most influential in their effects on output uncertainty. These abilities allow TAF to provide important information on future research priorities and the confidence in current estimates of acid deposition damages and Title IV benefits.

In a further effort to share TAF-related research, information on the TAF project, including draft models and the Analytica modeling software, is being made available over the World Wide Web via the Internet (http://www.lumina.com/taflist). In addition, examples of TAF used as an analytical tool appear in Palmer and Burtraw as well as in Shannon et al.

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RAISON

The National Water Research Institute of Environment Canada has developed a model to support environmental decision makers. The Regional Analysis by Intelligent Systems on Computer (RAISON) system is designed for a teamwork approach to developing decision-support systems for various environmental problems. The teamwork approach considers not just the software but also the scientists and end users who must be involved in the development from an early stage. The RAISON prototype is sufficiently robust to interact with scientists and policy advisors, first to overcome any communication problems among themselves and with the computer, and then to iteratively improve the system toward creating a useful final product. While RAISON has some similarities to geographic information systems (GIS), it differs significantly insofar as it emphasizes decision support and analysis that are difficult or impossible in a typical GIS.

RAISON offers a generic framework to integrate data, text, maps, satellite images, pictures, video, and other knowledge input. The system provides the user with a library of software functions and tools—including algorithms, models, optimization procedures, expert systems, neural network, and other information technologies—to produce customized interfaces and output, including interpretation, advice, scenario tests, strategic analysis, and policy recommendations. For example, data can be entered into RAISON through conversion interfaces available for many off-the-shelf databases. GIS maps can be entered in vector and raster formats. Models can be incorporated into the system by: (1) using the codes as given if compatible with the programming languages used in RAISON (Visual Basic, Visual C, C++), (2) building an interface that intercepts the input and output to connect to the database in RAISON, or (3) executing the model off-line but writing and reading the input and output. By using the various modules in RAISON (since all components are linked via graphical interfaces), scientists and policy advisors can adapt different applications with customized interfaces using optimization procedures or expert system techniques to direct control of the information and knowledge.

The RAISON system is property of the Government of Canada. It is distributed under license by NWRI Software. For further details, please consult the references, or contact:

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Fax: (905) 336-4582
Email: david.lam@cciw.ca

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RAINS–Asia

Expanded energy use in Asia, combined with use of indigenous coal, will result in an increase in emissions of acidifying compounds and greenhouse gases. By the year 2010, SO_2 emissions from Asia will most likely exceed the emissions of North America and Europe combined.

In recent years, integrated assessment models have been used for international negotiations on acid deposition in Europe and North America. These models provide negotiators and regulators with a full regional picture of the problems associated with the entire causal process, from energy systems and emissions to the ultimate impact on the natural and man-made environment. The model user can analyze the regional and national implications of various scenarios, which include options for energy use, control strategies, and mitigation policies.

The Regional Air Pollution Information and Simulation (RAINS)–Asia model is a tool for integrated analysis of air pollution. It consists of three modules: (1) Resource and Energy Scenario Generator, (2) Energy Emissions, and (3) Deposition and Critical Loads Assessment. Each module describes various aspects of acidifying emissions and dry and wet deposition. A set of menus and options guides users through the modules.

The three modules together permit users to operate the PC-based RAINS–Asia policy model in a scenario-analysis mode. They can estimate current costs and impacts of alternative emission control strategies on a country or regional basis. Emissions can be tracked through the deposition process to assess their potential impacts on critical ecosystems. Control strategies can be specified for specific fuel types, economic sectors, emission-generating power plants, emission control technologies, and regions or countries under study, and they can be applied individually or in any combination. The model can also be used to identify potential maximum impact locations for establishing monitoring sites, which in turn could assist in model validation.

RAINS–Asia covers East, South, and Southeast Asia, with particular emphasis on Japan, India, China, Indonesia, Thailand, and South Korea. It contains databases on energy consumption for 23 countries, 94 subregions, and 250 large point sources of deposition, and estimates the acid deposition carrying capacity of 31 types of ecosystems. Values for sulfur depositions are based on a yearly average and are calculated at a 1 x 1 degree of resolution. Aggregate results of source–receptor information on acid deposition patterns for each subregion or country can be obtained, and local impacts can be estimated as well. The temporal range of the model is 1990–2020.

Resource and Energy Scenario Generator (RESGEN)

Based on best-estimate assumptions of economic development and population growth, RESGEN makes possible the generation of scenarios of energy consumption pathways. Energy consumption is disaggregated into industrial, transportation, residential, commercial, and other sectors. The supply side of the module identifies different technologies for energy generation and sources of emissions, such as electricity generation, oil refining, and other energy-sector operations with combustion of fossil fuels. This framework makes it possible to generate rough estimates of future energy demand and supply trends under a variety of socioeconomic and technical assumptions.

Energy Emissions (ENEM)

The ENEM module takes the energy consumption scenarios at the sectoral and regional levels, as given by the RESGEN module, and estimates the corresponding SO_2 emissions and costs of various emission control options. Sulfur emissions from combustion of fossil fuels are calculated based on fuel characteristics, combustion technology, and emission control assumptions. Emissions are characterized as low-level area sources and high-level large point sources. The module considers a number of options to reduce sulfur emissions, including fuel desulfurization and flue-gas desulfurization. To explore integrated abatement strategies, the users can apply specific control policies to selected countries or regions within countries. The results of energy-conservation measures and fuel substitution can be explored by analyzing alternative energy pathways, either by selecting one of the several preset energy-use scenarios or by creating a new scenario based on expectations of fuel use.

Emission control and associated costs are based on the most commonly used emission control technologies. Cost evaluation is based on international operating experiences of pollution control equipment, and extrapolating them to country context. It is assumed that a relatively free and competitive market exists for control technology. This module also computes national cost curves that rank abatement measures by their cost-effectiveness.

Deposition and Critical Loads Assessment (DEP)

This module estimates ambient levels of acid deposition precursors and acid deposition throughout the region and compares them with data on environmental sensitivities that are presented in the form of critical-load maps. This module consists of two submodules: Atmospheric Transportation and Deposition and Ecosystems Impact.

Atmospheric Transportation and Deposition (ATMOS)

The ATMOS submodule is based on the National Oceanic and Atmospheric Administration's Branching Atmospheric Trajectory (BAT) model, which calculates wet and dry deposition of SO_2 and sulfates from a particular source as the pollutant is transported by meteorological fields. If these trajectories are run for an entire year, then the submodule estimates the amount of annual deposition on the entire region from a particular source. If the calculations are repeated for all sources, then the total annual deposition in the region can be estimated. Inputs for this submodule include SO_2 emission rates, winds and temperature, precipitation rates, and estimates of dispersion coefficients, dry deposition velocities, and wet-scavenging coefficients. The module is run for each large point source and area source estimated by ENEM, and sulfur deposition is calculated on a 1 x 1 grid. The results are aggregated to provide source–receptor information on acid deposition patterns for each of the subregions in the study region, and further aggregated to provide country-by-country source–receptor information.

Ecosystems Impact (IMPACT)

The IMPACT submodule estimates critical loads (the maximum long-term deposition levels that could be tolerated without damage) for 14 different ecosystems (see footnote). The critical loads are compared with

Desert/semi-desert, mangrove woods, irrigated land/paddy, semi-arid and thorn woods, dry tropical/subtropical/savanna, agriculture, cool scrub/grassland, temperate broadleaf wood, tropical montane forest, other conifer trees, bog/mire/moor, wet tropical forest, Tibetan cold grass, northern/main/southern taiga/tundra.

the estimates of sulfur deposition from the ATMOS submodule to determine which ecosystems may be at risk for different emission scenarios. This assessment is based on complex dynamics of processes in key ecosystems, such as soils, surface waters, and vegetation systems. These models include the computation of the depletion of acid buffer capacity of ecosystems under the influence of precipitation, evaporation, water flows, and budgets of chemical ecosystem constituents.

The critical-load calculation involves a two-step process. The first step applies a qualitative relative-sensitivity approach to distinguish an ecosystem's sensitivity to acidification. In this method, weights are assigned to four indicators of ecosystem sensitivity—bedrock lithology, soil type, land use, and annual rainfall. In the second step, based on the Steady-State Mass Balance Method, computations are performed to assign critical loads to all areas distinguished on the map of relative sensitivities. This method assumes steady-state equilibrium between soil solid phase and soil solution, and computes the maximum acid input to the system that will not cause an excess of the critical alkalinity value, which is computed from average thresholds for chemical values, such as pH, aluminum, and aluminum-calcium ratios.

Weathering rate, which is a key input to the process, is determined by estimates of soil mineralogy, which are then modified by climate and soil attributes. The resulting map of weathering rates and ratios of land use and precipitation to potential evapotranspiration are used in the critical-load calculations.

Issue-Specific Models

A need has arisen to test the veracity of model projections, especially in cases where policy and/or economic interests are at stake. As Oreskes et al. (1994) pointed out, however, verification and validation of mathematical models of natural systems are impossible, because natural systems are never closed, and model results are not unique. Model confirmation is possible and entails demonstration of agreement between prediction and observation. Because such confirmation is inherently partial, it is critical that policy-relevant models be tested in a variety of settings and under a variety of conditions.

MAGIC

Since 1990, the Model of Acidification of Groundwater in Catchments (MAGIC) (Cosby et al., 1985) has been widely used throughout North America and Europe. It has been the principal model used by NAPAP to project the response of surface waters to changing levels of sulfur deposition. MAGIC projections of the effects on surface water chemistry of various sulfur emission scenarios formed the technical foundation for a large part of NAPAP's *1990 Integrated Assessment Report* (NAPAP, 1991). Subsequently, a research effort was conducted from 1990 to 1996 to improve the performance of MAGIC and to test the model and confirm its results at multiple sites. Model evaluations have included hindcast comparisons with diatom reconstructions (see footnote) of preindustrial lake water chemistry in the Adirondack Mountains of New York, and tests of the veracity of model forecasts using the results of whole-catchment acidification experiments in Maine (Norton et al., 1992) and Norway (Gjessing, 1992) and whole-catchment acid-exclusion experiments in Norway (Wright et al., 1993).

Based on the results of this testing, it appears that MAGIC provides reasonably accurate forecasts of changes in surface water acid-base chemistry in response to changing levels of acid deposition. Although some uncertainties remain, particularly with respect to watershed nitrogen dynamics, MAGIC provides a generally accurate and well-tested tool for integrated assessment modeling.

The testing of MAGIC over the last six years has elucidated several potentially important deficiencies in structure and method of application, and has resulted in changes to the model and its calibration procedures. The work has included in-depth evaluation of issues related to regional aggregation of soils data, background sulfur deposition, natural organic acidity, nitrogen, and aluminum mobilization. The result has been an improved and more thoroughly tested version of MAGIC, which yields forecasts different from the version that served as the technical foundation for NAPAP's *1990 Integrated Assessment Report.*

Changes to the Model

Background Sulfate and Subregional Calibration

Subsequent to the regional MAGIC modeling that was conducted for NAPAP (1991), there was concern that

Diatoms are microscopic algae, whose remains are incorporated into lake sediments that accumulate over time. The species composition and relative abundance of diatoms at different levels in the sediment can be used to estimate the pH of lake water using sophisticated mathematical relationships.

(subregional) Adirondack soils might differ in their chemical properties from related (regional) soils in other areas of the Northeast, and that MAGIC projections for Adirondack watersheds might be biased because they were based on soil attributes that actually reflected conditions in the Northeast other than those in the Adirondacks. Therefore, the model input data were reaggregated to use only soil collected from Adirondack sites.

Modeling for the *1990 Integrated Assessment Report* also assumed that the deposition of sulfur in preindustrial times was limited to sea salt contributions. Based on analyses presented by Husar et al. (1991), this assumption was modified so that preindustrial deposition of sulfate was assumed to be equal to 13% of current values (Sullivan et al., 1991).

Recalibration of MAGIC to the Adirondack lakes database using the regionally corrected soil and background sulfate data resulted in approximately 10 μeq L^{-1} lower model estimates of current acid-neutralizing capacity. A substantial downward shift was also observed in predicted preindustrial and current lake water pH (~ 0.25 pH units) for lakes having current pH greater than about 5.5. These differences were attributed to lower calibrated values for lake water sulfate concentrations and higher values for the partial pressure of carbon dioxide estimated for Adirondack lakes, compared with the Northeast as a whole (Sullivan et al., 1991).

Organic Acids

Concern was raised subsequent to the *1990 Integrated Assessment Report* regarding potential bias from the failure to include organic acids in the MAGIC formulations used by NAPAP (1991). MAGIC hindcasts of preindustrial lake water pH showed poor agreement with diatom-inferences of preindustrial pH, and preliminary analyses suggested that these differences could be partly due to the presence of naturally occurring organic acids in Adirondack lake waters.

An organic acid model was developed by Driscoll et al. (1994) using data collected by the Adirondack Lakes Survey Corporation (Kretser et al., 1989) for 1,400 lakes located in the Adirondack region. This model was coupled with MAGIC. Model hindcasts using the unmodified MAGIC yielded preindustrial pH values that were substantially higher than diatom-based estimates, and the discrepancy was greatest for those lakes in the most biologically sensitive portion of the pH range (pH of 5.0 to 6.0). Furthermore, MAGIC hindcast pH estimates were greater than 6.0 for all lakes investigated, whereas diatom estimates of preindustrial pH ranged from as low as 5.2 to above 7.0. When the organic acid model was incorporated into MAGIC and simulated preindustrial pH values from the new model were compared with diatom-inferred pH, the comparison yielded considerably closer agreement between model estimates of preindustrial pH than did the simulations that did not consider the effects of organic acids (Sullivan, Cosby et al., 1996).

When organic acids were omitted from the analysis, the lakes of greatest relevance with respect to potential biological effects of acidification, especially those having a pH of less than 5.5, exhibited increasingly larger discrepancies with decreasing pH between diatom and MAGIC model estimates of preindustrial pH. Including an organic acid representation in the MAGIC simulations greatly improved the agreement between these two modeling approaches.

The results of these analyses of Adirondack lakes demonstrated that: (1) organic acids must be considered in modeling the response of lake waters in the Adirondack Mountains (and possibly other regions) to acid deposition; and (2) once organic acids are included in the modeling approach, reasonable agreement is obtained in hindcast comparisons with diatom-inferred pH. It should be emphasized, however, that this test included only two points in time and involved only pH. Even though the model adjustment with organic acids improved agreement for pH, other variables in the model may have been poorly represented. MAGIC and other process models require further testing and confirmation. Many potentially important geochemical processes are not well represented in the model or the input data, and it was not clear how inclusion of such processes might affect model results.

Aluminum

Aluminum mobilization is now widely believed to be one of the most important ecological effects of surface water acidification. Potential effects of aluminum mobilization from soils to surface and soil waters include alterations in nutrient cycling, pH buffering effects, and toxicity to aquatic biota and terrestrial vegetation.

MAGIC simulates aluminum solubility based on an assumed equilibrium with the mineral gibbsite. The model first calculates the total concentration of acidic cations (e.g., hydrogen plus aluminum) on the basis of simulated concentrations of base cations and mineral acid anions (e.g., sulfate, nitrate, chloride) using mass balance and electroneutrality constraints. The acidic cations are then partitioned between hydrogen and aluminum, using the gibbsite mineral equilibrium, thermodynamic equations, the partial pressure of carbon dioxide, and the organic acid formulation. This partitioning is important because inorganic aluminum in solution can be highly toxic to aquatic biota, even at low concentrations (Baker and Schofield, 1982).

Model simulations often overpredict the change in aluminum concentration. The aluminum formulation in the MAGIC model has recently been modified to better reflect empirical relationships between aluminum and hydrogen ion. The revised formulation was used to predict aluminum concentrations in runoff at experimental ecosystem manipulation sites in Maine and Norway. In both cases, it yielded closer agreement with measured values than the original MAGIC predictions (Sullivan and Cosby, in press).

Nitrogen

MAGIC contains an extremely simplified representation of nitrogen dynamics within catchment soils. There are no processes controlling the details of nitrogen cycling in the model. The version of MAGIC used for NAPAP's *1990 Integrated Assessment Report* was not appropriate for simulation of changes in atmospheric deposition of nitrogen. In light of the increasing concern about nitrogen saturation in forested ecosystems, this was a serious shortcoming in the model.

A new, coupled sulfur and nitrogen model, MAGIC-WAND, was developed by extending MAGIC to incorporate the major ecosystem nitrogen fluxes and their changes through time (Ferrier et al., 1995). MAGIC-WAND is perhaps the most generalized model, but several more detailed nitrogen models are also available, including MERLIN, NuCM, and PNET-CN. MAGIC-WAND has been applied regionally to simulate the response of lakes in the Galloway region of southwestern Scotland to changing deposition of sulfur and nitrogen from 1988 to 1993. The model is currently being further evaluated for watersheds in the southern Appalachian, Cascade, and Rocky Mountain regions of the United States.

Cumulative Impacts to Changes to MAGIC

The improved MAGIC predicts that sensitive lakes and watersheds in the Adirondack Mountains are less responsive (in terms of change in acid-neutralizing capacity, pH, and inorganic aluminum) than was predicted by the earlier version of MAGIC used for NAPAP's *1990 Integrated Assessment Report.*

To evaluate the incremental and cumulative impacts of the modifications to MAGIC, Sullivan and Cosby (1995) conducted a suite of model simulations for the Adirondack Direct/Delayed Response Project (DDRP) lakes. They used the baseline model structure from the DDRP and the *1990 Integrated Assessment Report*. The changes to the model they examined included modifying the assumption regarding background sulfur deposition, reaggregating the soils data, recalibrating the model specifically for the Adirondack subregion, adding the organic acid model to the surface water compartment, and changing the aluminum/hydrogen ion relationship from cubic to quadratic. However, these analyses did not examine the effects on model output of including nitrogen dynamics in the model simulations.

A suite of simulations was conducted based on the application of an assumed deposition scenario to derive a 50-year forecast using each model structure. The deposition scenario assumed constant sulfur deposition from 1984 (the calibration year) to 1994, followed by a 30% decrease in sulfur deposition from 1995 to 2009, with constant deposition thereafter until 2034. The modeled responses of 33 Adirondack lakes to this scenario were also considered. The impacts of the changes were illustrated by tabulating the percentage of lakes predicted to have pH, acid-neutralizing capacity, or aluminum values in excess of commonly accepted thresholds of potential biological effects.

The overall effect of the various changes to the model structure and application procedures was an increase in the percentage of lakes exceeding various biological thresholds with respect to pH, aluminum, and acid-neutralizing capacity subsequent to an hypothesized 30% decrease in sulfur deposition (Table A-1). The largest changes were observed for pH and aluminum; acid-neutralizing capacity projections were less affected. The modifications to the model that caused the greatest changes in projected output were the recalibration of the model to the Adirondack subregion, modification of the assumption regarding background sulfate, and the incorporation of the organic acid model into MAGIC. The modification of the aluminum caused fewer lakes to be projected to exceed aluminum threshold values in response to the reduced deposition scenario; this change was quantitatively less important than the previous changes.

Table A-1

Cumulative Effects of Post–1990 Changes to MAGIC

Data Type	% of Lakes with pH Below: 5	5.5 (acidity)	6	% of Lakes with ANC Below: 0	25 (μeqL $^{-1}$)	50	% of Lakes with Al Above: 50	100 (μeqL $^{-1}$)	200
Measured 1984 Values	12%	32%	38%	18%	48%	59%	30%	18%	10%
MAGIC Projections of 2034:									
1990 Version of MAGIC Used for NAPAP	0%	8%	20%	6%	34%	44%	4%	0%	0%
Current Version of MAGIC*	8%	32%	44%	14%	40%	44%	30%	10%	4%

Does not include nitrogen dynamics, which are included in MAGIC-WAND.
Source:Sullivan and Cosby, 1995

The magnitude of effect of the cumulative modifications to the model was considerable. For example, 32% of the lakes had measured pH less than 5.5 in 1984, whereas only 8% were projected to still have pH less than 5.5 after the reduction in sulfur deposition, using the earlier version of MAGIC used for the *1990 Integrated Assessment Report*. In contrast, the improved version of MAGIC projected that 32% of lakes would still have pH less than 5.5 in the year 2034. Similarly, of the 30% with measured inorganic aluminum concentrations greater than 50 μg L^{-1} in 1986, the original model structure projected only 4% would still have concentrations greater than 50 μg L^{-1} in 2034, compared to 30% projected to continue to have high inorganic aluminum by the improved version of MAGIC. Based on model projections using the improved version of MAGIC, little recovery of Adirondack lakes would be expected subsequent to a 30% reduction in sulfur deposition. The number of lakes having pH lower than 6.0 was actually projected to increase, and the number of lakes projected to have acid-neutralizing capacity lower than zero only decreased slightly in response to lower deposition. These estimates were independent of any possible increases in nitrate leaching that might occur. The lack of recovery suggested by these revised model projections is attributable partly to a decrease in the modeled base saturation of watershed soils. These results may affect expectations of recovery in response to sulfur emission controls mandated by Title IV.

The future response of lakes and streams to acid deposition is also highly dependent on the extent to which watersheds in acid-sensitive regions become nitrogen-saturated. EPA scientists conducted MAGIC simulations for 50 years into the future that effectively bounded the range of possible water chemistry responses—ranging from no watersheds reaching nitrogen saturation to all simulated watersheds reaching nitrogen saturation during the simulation period. The model projections for Adirondack lakes, for example, suggested that the percent of chronically acidic lakes in the target population in 50 years could range from 11% to 43%, depending on the number of watersheds that become nitrogen saturated (U.S. EPA, 1995). Similarly, for mid-Appalachian streams, the modeled percent of streams acidic in 50 years ranged from 0% to 9%, depending on the extent of nitrogen saturation (U.S. EPA, 1995).

Magic Model Confirmation

MAGIC has been tested after inclusion of many of the model modifications discussed in the preceding sections. The revised model with Driscoll et al.'s (1994) organic acid model yielded reasonable agreement between model hindcast pH and diatom-inferred pH for the data set of 33 Adirondack lakes. Differences between diatom and MAGIC estimates of preindustrial pH of Adirondack lakes, based on the version of MAGIC that includes an organic acid representation, were well within the range of expected differences due to annual and seasonal variability and uncertainties in the model algorithms.

However, "successful" comparison of MAGIC with diatom hindcasts in one region does not constitute a sufficient verification to impart complete confidence in using MAGIC, or any process model, for predicting the response of surface water chemistry to changes in acidic inputs. Additional model confirmation in the form of comparison of model output with measured data is required. This has been the focus of modeling efforts at the experimental manipulation site at Bear Brook Lake in Maine and at two sites in Norway.

Initial modeling efforts at Bear Brook (Norton et al., 1992; Sullivan et al., 1994; Cosby et al., 1996) predicted a much larger increase in stream water sulfate concentration than was observed in the treated stream. Although there is considerable uncertainty regarding the lag in sulfate release/adsorption in soils, it appears that MAGIC overpredicted the increase in stream water sulfate concentrations at Bear Brook by nearly a factor of two. This overprediction was due to the high value assumed for the half saturation of sulfur adsorption, which was based on laboratory measurements. As a consequence, other key variables (especially acid-neutralizing capacity and aluminum) were also predicted to increase to a greater degree in response to the experimental acidification than was actually observed.

The original calibration of MAGIC for the Bear Brook forecast was based on four years of data from the reference stream, East Bear Brook. To assess the degree to which discrepancies between predicted and observed stream water chemistry at Bear Brook could be improved by correcting the error in predicting sulfur dynamics and *a priori* differences between treatment and control catchments, a revised calibration was conducted. The revised calibration corrected for the obvious large bias in effective sulfur adsorption in watershed soils and also corrected for *a priori* differences between the treatment and reference catchments. In essence, in the latter case, expert judgment was substituted for strictly laboratory-derived information. The resulting simulations matched measured values in West Bear Brook to a substantially greater degree than the earlier forecasts.

Projected stream water sulfate concentrations closely agreed with measured values in West Bear Brook for the first three years of manipulation in the revised model simulation (Cosby et al., 1996). The model simulation also showed much better agreement with measured values for the sum of base cations and acid-neutralizing capacity, than the initial MAGIC simulation. Although the effects of a drought year (1992) on base cation concentrations and acid-neutralizing capacity were still not captured by the simulation, the overall agreement between predicted and observed base cation concentrations and acid-neutralizing capacity was much improved. Slight underestimation of pH decrease and overestimation of aluminum increase were still evident in the revised projections, although the magnitudes of these biases were reduced dramatically because of the improvement in predicted sulfate concentration and acid-neutralizing capacity.

Results of modeling efforts at Bear Brook, as well as measured chemical changes at Bear Brook, illustrate that a remaining major weakness of MAGIC (and other process models) relative to the needs of NAPAP is the failure to include algorithms to simulate nitrogen cycling and nitrogen retention in watershed soils and vegetation. The success of the nitrogen component of the modeling effort at Bear Brook was totally dependent on adjusting the nitrogen inputs to the model to match measured outputs in stream water. Nitrogen dynamics were extremely important at this site (Kahl et al., 1993), although this had not been anticipated at the inception of the Watershed Manipulation Project at Bear Brook.

The process of evaluating and improving MAGIC is iterative. It has now been shown that the inclusion of organic acids in the model is important and that MAGIC often yields acceptable model simulations of past and future change. It has also been shown that further improvements are needed, particularly with respect to nitrogen, which is the focus of the extended version of the model MAGIC-WAND. The model simulations at Bear Brook also revealed important weaknesses and uncertainties in several aspects of the model structure and/or the manner in which the model is applied to a given catchment. Results at Bear Brook verified that key remaining uncertainties relate to the modeling of aluminum dissolution, sulfur retention in soils, and the dependence of runoff chemistry on hydrological variations that are difficult to simulate.

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Appendix B

Design and Performance of Pollution Trading Programs

Control of SO_2 emissions under the 1990 Clean Air Act Amendments instituted two important innovations in U.S. environmental policy. The more widely acknowledged of these is the SO_2 emission trading program. Less acknowledged is the average annual cap on aggregate emissions by electric utilities, which guarantees that nationwide emissions will not increase as economic growth occurs in the future.

The two innovations are designed to work together. Firms are allocated annual SO_2 emission "allowances" in proportion to their historic emissions, which they may transfer among facilities or "bank" for future use. Under this approach, the environmental goal emissions cap is established in the statute, but the means for accomplishing that goal is left to the ingenuity of the interested parties. In addition, each affected plant must continue to meet all other applicable state and federal emission standards.

The main attraction of a permit trading program or, more generally, of what is known as an incentive-based approach to environmental regulation, is the promise that it can achieve an environmental goal at a lower cost than regulatory approaches that dictate specific actions for individual facilities or groups of facilities. Because the cost of reducing emissions often varies tremendously among facilities, trading programs can help ensure that the least expensive means are pursued before undertaking more costly efforts. The savings can be a boon for consumers and industry by reducing the cost of regulation, and a boon for the environment by allowing society to purchase greater environmental protection at the same cost. The evidence to date for the SO_2 emission trading program indicates that the cost savings have been substantial.

A second type of cost savings from incentive-based regulation are those that are expected to be achieved over time as firms find ways to lower the cost of reducing their emissions. Emission trading provides incentives for firms to innovate because firms can expect to keep the cost savings. At this juncture it is premature to say whether significant innovation has resulted from the SO_2 program, but there are many anecdotes of process changes and efficiency improvements that have contributed to the low cost of emission reductions to date. It can be said at this point that competition between different methods of compliance has lowered the cost of compliance.

With the apparent success of the SO_2 trading program, the question arises whether this approach should be used to guide other environmental protection efforts. To be sure, there are other environmental problems that would seem to lend themselves to the use of one or another incentive-based approaches, such as tradable permits, emission fees, or deposit-refund systems. However, there are also a variety of problems that are less well suited. This appendix considers the characteristics of environmental problems in general that may or may not be amenable to this approach, especially in the context of controlling air pollution. It evaluates why the SO_2 problem appears well suited to the use of tradable permits, and describes new applications of incentive-based approaches for controlling CO_2 and NO_X.

Characteristics That Contribute to the Success of Permit Trading Programs

Emission permits are similar in many ways to other goods traded in markets. The success of the market for emission permits depends on the breadth of supply and demand. The larger the number of firms that can trade pollution permits the more successful a trading program will be in reducing control costs.

Paradoxically, while the participation of many firms makes it easier for buyers and sellers to find each other, it also makes it easier for them to remain anonymous. Firms may want to remain anonymous when it comes to trading permits because they do not want to signal to competitors their plans for the future. In a small permit market, the actions of one firm are easily recognized by its competitors. In a large permit market, it is less likely that any one firm can dominate the market. Most important, the greater the number and diversity of firms, the greater is the likelihood that there will be differences among firms in the cost of reducing emissions and, hence, greater potential gains from trading.

While a greater number of participants may offer greater potential cost savings, it also makes monitoring and enforcement more difficult. In cases where regulators cannot measure emissions accurately—either because of technological limitations or because there are a very large number of emitters (e.g., small sources and automobiles)—they are likely to prefer specific technology controls to incentive-based approaches. Technology standards ensure that the concentrations of pollution from a facility will meet the design value of the controls in place. The drawback, however, is that since the use of the facility or vehicle may vary, this approach will not allow regulators to achieve a cap on the total volume of emissions.

The environmental consequences of pollution may depend on where and when emissions occur. For some pollutants, a ton of emissions will have basically the same effect on the environment, regardless of its location or source. These types of pollutants are called “uniformly mixing,” and their homogeneity broadens the potential market by expanding the realm for trades among greater numbers of emitters. Ozone-depleting substances and greenhouse gases are good examples of uniformly mixing air pollutants, because their effects on the environment do not depend on the individual sources of emissions.

On the other hand, many pollution problems have important local attributes. For example, NO_X emissions contribute to ground-level ozone, which is a local and, sometimes, a regional problem. The role of NO_X in ozone creation depends not only on where emissions occur, but also on the presence of other pollutants and on the season and the time of day when emissions occur. At the same time, NO_X emissions contribute to other environmental problems—such as particulate pollution and nitrogen deposition—that have distinct spatial characteristics.

Incentive-based approaches, such as tradable permits, can be designed to overcome local concerns in a variety of ways. A trading program may restrict trading between geographic zones, or may allow trading among zones at ratios that reflect the relative environmental damage that results from a unit of emissions at each location. Similarly, concerns about the timing of emissions can be addressed through trading rules that restrict increases in emissions during certain time periods. In some cases, these approaches have been applied successfully. However, experience has shown that restrictions on trading programs detract from their likely success because they limit the breadth or scope of the market and raise transaction costs.

In considering the applicability of trading programs to various pollution problems, there appears to be a simple trade-off. The more localized over space or time the environmental effect of concern is, the smaller the potential market will be, and the less likely trading programs will offer significant potential cost savings.

On the other hand, experience suggests that it is not always necessary to allow local concerns about the spatial and temporal effects of emissions to narrowly determine the ultimate design of a trading program. In some cases, the cost savings from a broader-scale, less encumbered trading program outweigh local environmental concerns and ultimately lead to net gains for environmental protection. Moreover, in some cases very simple safeguards are sufficient to protect against most adverse local effects, while not significantly restricting the scope for trading. For example, although the local effects of some pollutants vary greatly, the lion’s share of this variation may be controlled by a simple system of trading zones that generally limits the pattern of trading.

Elements That Led to the Success of the SO_2 Program

Several features of the SO_2 problem make it a good candidate for a permit trading program. Among these is the large number of electricity-generation facilities that are responsible for a significant majority of all SO_2 emissions and that provide ample potential buyers and sellers of pollution permits. The physical differences among these facilities and their fuels correspond to the great variation in the cost—and cost-saving opportunities—of reducing emissions.

An interesting feature of the SO_2 program is that it is a national trading program, absent restrictions on trading between or among facilities in different locations. However, the environmental problems caused by SO_2 are regional and relate to the geographic source of emissions. For instance, due to wind patterns, emissions from a coal-fired power plant in the Ohio Valley make a greater contribution to acidification of the Adirondacks than do emissions from a plant in Mississippi.

By treating all emissions equally, the program has extended the breadth of the market and has opened up greater opportunities for trading. The presumption is that opportunities to reduce costs and to apply those savings to achieve greater emission reductions outweigh the possibility that pollution control will be greater or less in some locations than in others. Any differentiation in the benefits in local areas should be measured against this substantial reduction overall.

The program also affords significant potential cost savings by allowing sources of SO_2 emissions to bank their emission reductions in one period to offset necessary future reductions. Environmental problems associated with SO_2 emissions are not particularly sensitive to the timing of emissions. For example, the ecological impacts of acidification are primarily the result of accumulated deposition of sulfur. The secondary particulates that cause health effects are evident in the atmosphere for time periods that extend over several days, which also helps to mitigate the effects of changes in emissions at a particular time.

One further important ingredient in the successful formula for SO_2 trading is the availability of continuous emissions monitoring systems, which provide a means to ensure compliance when regulators are not sure what actions should be taken by individual firms. Indeed, compliance has been achieved by 100% of facilities affected under the first two years of the Title IV program.

Closely Related Experiments

Several closely related experiments on a somewhat smaller scale also provide lessons about the potential viability of permit trading programs in different settings. One of the earliest and most successful was the program to phase out lead in gasoline.

In the 1980s, EPA set a schedule to virtually eliminate lead in gasoline. To achieve this schedule, it allowed trading among refineries in order to obtain an average lead content in gasoline specified in their 1983-1987 phase-out time schedule. The program also allowed refineries to bank their lead rights, so that a refiner could lower the average lead content of its fuels ahead of schedule in order to fall behind schedule at a later point in time.

The primary success in the case of the lead phase-out, as in the case of any environmental program, rests in achieving its environmental goal. However, the trading aspect of the phase-out program contributed to this success because it helped to reduce the cost of achieving the environmental goal and, in so doing, helped build consensus among industry and consumers for the viability of that goal. Environmental concerns were not significantly affected by the program, and monitoring lead content and measuring performance were straightforward. Further, although some variation in the timing and geography of emissions inevitably resulted under the program, there is no evidence that it was significant.

Another closely related experiment is the phase-down of chlorofluorocarbons and halons—collectively described as ozone-depleting chemicals—under international agreements to which the United States has been a signatory. The ultimate goal is to phase out or severely limit the use of these chemicals. To achieve this goal, EPA issued regulations to control both the production and the consumption of ozone-depleting chemicals through a quota system that allocated tradable quotas to producers and consumers in proportion to their historic levels of use. Producers need to use both types of allowances, while importers only need to use consumption allowances. Allowances may be traded domestically or internationally among signatory countries.

An interesting aspect of this phase out was concern that the decreasing availability of ozone-depleting chemicals would raise their profitability. In response, Congress imposed a tax on these chemicals in part to capture some of the windfalls that would result from their increased scarcity, and also to promote development of substitutes.

The ozone-depleting chemical program is widely viewed as a success. The cost of the phase-out has not been exorbitant, due in part to the large number of substitutes that have been brought to the market, allowing the phase-out schedule to be moved forward in some cases. One class of ozone-depleting chemicals was eliminated in 1996, except for very limited uses. A second class of chemicals is to be phased out in the early decades of the next century.

A third experiment that has been repeated in a number of local settings is the use of emission-reduction credits for criteria air pollutants. These experiments have taken a number of forms. “Offset” programs allow a new source of emissions locating in an urban area in violation of the National Ambient Air Quality Standards to obtain “offsets” for new emissions by reducing emissions at older sources. The “bubble” program allows new or modified emission sources to avoid stricter new source performance standards as long as total emissions from an entire industrial facility do not increase as a result of the changes. In some cases, emission reduction credits may be “banked” for subsequent use.

Most analyses of the numerous efforts to promote local emission reduction credit programs have concluded that the programs have fallen short of their expectations. One reason is the programs have had to accommodate the geographic and time-sensitive nature of emissions of criteria air pollutants in urban nonattainment areas. Also, there has been concern that offsets may be generated from reduced activity at facilities that were about to shut down anyway, and that trading a credit to a new facility effectively increased emissions in an urban area. The result of these concerns has been a variety of controls on the nature of trading that limit the scope of the market, effectively raising transaction costs and reducing the volume of trading.

Programs other than emission-reduction credit programs are geared toward controlling the total quality of emissions. For instance, both the SO_2 and ozone-depleting chemicals programs cap overall emissions. The lead phase-out program comes close to doing the same thing because there was expected to be relatively little variation in refinery production over the brief period when the phase-out was achieved. However, the emission-reduction credit programs are calibrated with emission rates (tons of pollutant per volume of output), rather than emission quantities (tons of pollutant per year). This provides no guarantee that emissions will not increase with intensified economic activity.

Such a possibility meant the program had to impose additional constraints to make sure emissions remain stable or decrease. These constraints undermined the performance of the emission-reduction credit programs to some extent. This approach was taken in many cases, since it was not possible for environmental agencies to consider the alternative approach of capping emission quantities. For many types of emission sources, monitoring of emissions has not been established, and an historic emissions profile is not known with which a baseline can be established, making an overall cap unattainable.

In general, as noted previously, one finds the greater the number and type of sources emitting a pollutant, the more difficult it is to monitor emissions. This makes it difficult to design an incentive-based approach to regulate emissions, and more likely that a traditional command-and-control approach will be necessary. Given the inability to monitor total emissions, regulators have relied on the use of specific technologies to ensure that emission rates are controlled, even though total emissions are not known or controlled with certainty.

New Applications of Emission Trading Programs

Two air pollution problems have recently attracted growing attention as potential new applications of emission trading programs. These two problems—CO_2 and NO_X emissions—are aligned at opposite ends of the spectrum with respect to the breadth of their environmental impacts. CO_2 emissions contribute to global climate change, regardless of their location. However, the contribution of NO_X emissions to pollution problems depends strategically on the timing and location of those emissions. Also, CO_2 emissions cannot readily be controlled through post-combustion abatement technologies, so emission reductions must be achieved through efficiency improvements and fuel switching. However, NO_X emissions can be controlled through abatement technologies, although significant opportunities also exist for efficiency improvements and fuel switching.

In other ways the two pollutants are similar. A significant portion of national emissions of both pollutants comes from large electricity-generating facilities and industrial facilities, which are easily monitored. However, a significant portion of both pollutants also comes from smaller sources, including vehicles, which are not easily monitored. Furthermore, in both cases there is tremendous variation in the costs of reducing emissions among the various sources, which provides considerable motivation to find ways to design trading programs that can overcome these obstacles.

The prospects for a CO_2 trading program were significantly bolstered by the Draft Protocol Framework for an international agreement proposed by the United States in January 1997. The protocol promotes the use of permit trading for CO_2 reductions among so-called Annex A and Annex B countries, which roughly correspond to the more developed economies. Furthermore, the draft protocol calls for expanded use of "joint implementation" between Annex A/B and other countries, allowing more-developed countries to invest in projects in less-developed countries to generate requisite CO_2 emission reductions. The prospect for the proposed CO_2 trading program is very uncertain at the time of this report's publication, as well as is the potential design for such a program. However, the differences in the cost of emission reductions among potentially affected sources and different countries is enormous. These differences argue strongly for designing a program that will allow the international community to reduce emissions more cost-effectively than uniform national approaches would allow.

At the other end of the spectrum are local experiments to reduce NO_X emissions. Previously established emission reduction credit programs for NO_X and other pollutants are delivering important cost savings. However, some of their conditions have prevented them from achieving widespread success. Also, as with the use of traditional technology standards, they cannot necessarily contain the level of emissions that result.

Increasingly, regulators are considering the use of cap and trading programs to explicitly limit the total quantity of emissions and to allow flexibility in attaining this goal. However, these trading programs must consider the local nature of the NO_X pollution—hence, calling for local or regional markets, sometimes with restrictions on the direction or timing of trading. Consequently, an emission trading program will produce less savings than a market covering a larger geographic area with more potential traders. Although, there are such a large number of potential sources of NO_X emission reductions (e.g., potential traders), that cost savings could still be great. Regulators are striving to design programs that maintain environmental safeguards while providing incentives to capture these potential savings.

Table B-1 provides a status report on a number of efforts to establish markets for NO_X trading. In some of these cases, regional markets have been established that are significantly large enough to overcome this geographic limitation. For instance, the RECLAIM program in Los Angeles has over 500 participants. Others, such as the Texas market, have been so small as to all but prevent trading between firms, though some trading among facilities within the same firm has occurred.

The regional nature of the environmental impacts of NO_X emissions also has restricted NO_X trading in other ways. The southern California RECLAIM and emerging Ontario, Canada markets can only trade in directions that reflect regional wind patterns. The Texas market has regional boundaries trades may not cross, and the proposed northeastern market may have similar barriers. These restrictions limit the amount of, and the corresponding potential gains from, trading.

As mentioned, NO_X emissions come from a wide variety of sources that include mobile and stationary emitters, small and large sources, and facilities that may be on the geographic fringe of the emission trading market. When many small and mobile sources exist in this market, it is difficult to include all of them because of problems in monitoring and administering the program. Nonetheless, in some cases, the small sources can contribute significant emissions to the local airshed. Therefore, regulators tend to rely on conventional approaches to control emissions from numerous, small sources, which typically control emission rates but not the overall level of emissions from these sources. Their exclusion from the trading program misses not only significant opportunities for cost savings, but also significant opportunities for emission reductions and, hence, is an issue attracting increasing attention.

Episodic constraints are also an important issue in NO_X trading markets. In contrast to the SO_2 emission trading market, some experts believe that the potential of emission "spikes" from NO_X are a key issue. Some markets have restrictions on the amount of trading or banking between seasons of the year. Additional episodic restrictions placed on NO_X trades include limitations on when banked credits may be used.

Table B-1

Status Report on Efforts to Establish NO_X Trading Markets

EXTENT OF MARKET	ALLOTMENTS/ BASELINE EMISSIONS
Chicago—Potential rules submitted in October 1996.	
The market originally included NO_X and VOCs. NO_X emissions were later dropped. The market runs from May 1 to September 30, covers the Chicago area (Cook, DuPage, Kane, Lake, McHenry, and Will counties) and only includes stationary sources. Facilities that emit more than 50 tons of NO_X per year must submit emission abatement plans by 1998; firms with 10 tons of NO_X emissions per year must submit plans by 1999.	Firms are given emission allotments measured against baseline emissions from the two highest ozone seasons from 1990 to 1997. This amount is reduced by 12% in 1999 and then reduced according to the State Implementation Plan.
Michigan—Market started in 1996.	
Established in 1996, this voluntary program for mobile and stationary sources includes VOCs, NO_X, and criteria pollutants. The market covers the entire state and includes all sources.	The baseline is determined as the average of two ozone seasons prior to the creation of the emission reduction credit.
Ontario, Canada—Trades have occurred, but the market is not yet official.	
The market includes NO_X and VOCs. It runs from April 1 to September 30 and is focused around the Windsor–Quebec corridor. There is a strong desire to have the market be similar to the Michigan market to promote cross-country trades.	Baselines are calculated relative to each company's specific process operations.
Northeast Ozone Transport Region (OTR)—Market is still in the planning stage.	
The market includes NO_X and VOCs and runs from May 1 to September 30. It includes CT, DC, DE, MA, MD, NH, NJ, NY, PA, VA, and VT. There is a possibility of expanding the market to include mobile sources.	Two possible scenarios: (1) A credit model that calculates an emission responsibility and a uniform emission rate for each facility. (2) A method where allocations are auctioned off or given away based on historical emissions. This historical allotment then becomes the baseline. Once the nature of the emission allotment is determined, the allotment is given to each state to decide how to allocate it within the state.
Southern California (RECLAIM)—Market started on January 1, 1994.	
The market currently includes all stationary sources that emit more that 4 tons of NO_X or SO_X per year. An extension of the market to include VOCs is planned. The market, which covers the Los Angeles basin, contains 535 sources of NO_X and SO_X.	Each facility is given an emission factor based on the type of facility. The initial allotment is calculated by multiplying the maximum throughput for each NO_X source from 1989 to 1992 by the applicable starting emission factor for that source. Once this is calculated, any additional reductions made from 1992 to 1994 are then added to the baseline level.
Texas—Stationary market started in 1992; mobile sources joined in 1995.	
The year-round market is currently open, but is in the process of designing cap and trade systems. It includes NO_X and VOCs mobile, area, and stationary sources. The market originally included the Houston–Galveston area, and has since expanded to include Beaumont and Dallas–Ft. Worth. As of March 3, 1997, only six intra-firm trades had occurred.	The initial allotment is based on a two-year average plus a standard deviation.

Program	BANKING AND EPISODIC CONSTRAINTS	SPATIAL CONSTRAINTS	NEW SOURCES
Chicago (continued)	Allotments are available for use during the season they are given out and during the following ozone season.	No spatial restrictions exist within market boundaries.	New sources will have to acquire allotments through the market. Small emitters must purchase allotments at a 1-to-1 ratio. Large emitters must purchase them at a 1.3-to-1 ratio.
Michigan (continued)	Banking is allowed for up to five years with no discounts for use during this period. Credits generated during the ozone season may be used at any time; credits generated outside of the ozone season may only be used outside of that season.	No spatial restrictions exist within market boundaries.	New sources must purchase allotments for 2.5 years.
Ontario, Canada (continued)	No external measure is placed on banked credits—no shelf life or discounts for future use. Same-season trades are not favored over inter-seasonal trades.	Trades involving more than 2,000 tons in a single ozone season may only follow the prevailing seasonal downwind pattern.	Two options: (1) government could hold additional allotments for new entrants, or (2) new entrants could be required to purchase allotments.
Northeast OTR (continued)	Unlimited banking of credits is allowed, with a price-based, progressive-flow control. The flow control is based on the number of credits banked. A certain number of credits may be used at a 1-to-1 ratio. After this level has been reached, the remaining credits may be extracted at a 2-to-1 ratio.	If the market is large enough and there is a sufficient amount of trading, then there should be no limits to the direction of trade. This issue will be revisited in three years.	New sources must follow all CAAA rules and purchase allotments either (1) from sources in the same nonattainment area or (2) from a source that is in a nonattainment area that has an equal or worse classification, or where the emissions from that area contribute to the National Ambient Air Quality Standard violations in the area where the facility will be located.
Southern California (RECLAIM) (continued)	Banking is not allowed due to the possibility of emission spikes. However, permits are allocated for overlapping time periods, providing one mechanism for short-run banking.	The Los Angeles basin is divided into two zones—coastal and inland. Trade is allowed within each zone and from the coastal zone to the inland zone. Trade is prohibited from the inner zone to the outer zone.	New firms must comply with best achievable control technology standards and must purchase offsets at a 1-to-1 ratio.
Texas (continued)	Emission reduction credits may be banked for up to 10 years. The shelf life of mobile emission reduction credits is a function of the vehicle mileage. All credits are discounted at 3% per year.	The unit that created the emission reduction credit must be in the same zone (Dallas–Ft. Worth, Beaumont, Houston–Galveston) as the unit that consumes the credit.	For the three areas, new facilities must comply with best achievable control technology standards. They currently do not need to purchase any additional offsets. However, this may change, depending on additional evidence regarding the effect of NO_X emissions on the production of ozone.

Appendix C

Interpretation of "Adverse" Effects for NAPAP Biennial Reports to Congress

Background

The 1990 Clean Air Act Amendments require that the National Acid Precipitation Assessment Program (NAPAP) prepare biennial reports to Congress, and that "every four years ... the report ... shall include the reduction in deposition rates that must be achieved in order to prevent adverse ecological effects" (Public Law 101-549, Title IX, Section 903 (j)(3)(F)(i), codified as amended at 42 USC §7403(j)(3)(F)(I)). This report is the first to address this requirement.

Although the term *adverse ecological effects* is not specifically defined in the Clean Air Act Amendments, a working definition can be derived from relevant statements at various locations in the statute. Congress expresses its concern with ecological components (the scope is broad and inclusive, since ecology encompasses the interrelationships of organisms and their environment) in the preceding subsection (E) of the statute. It requires reporting on "the status of ecosystems (including forest and surface waters) ... affected by acid deposition ... including changes in surface water quality and forest and soil conditions ... [and] high elevation watersheds" (42 USC §7403(j)(3)(E)(iii-v)). The adverse effects of concern to Congress, as evidenced in its findings and declaration of purpose, are the "dangers to the public health and welfare ... including injury ... damage ... and ... deterioration" (42 USC §7401(a)).

Working Definition

Based on the intent of Congress, as expressed above and elsewhere in the Clean Air Act Amendments, and shaped by indications of intent expressed in other relevant environmental statutes and regulations, the following working definition of *adverse ecological effects* has been derived and is used in the preparation of this report:

> any injury (i.e., loss of chemical or physical quality or viability) to any ecological or ecosystem component, up to and including at the regional level, over both long and short terms. Similarly, adverse effects for other areas of concern addressed in this report—i.e., visibility, materials, and human health—consist of loss of quality up to and including at the regional level, over both long and short terms.

Bases for Working Definition

Ecological components of concern to Congress are addressed in the Clean Air Act Amendments section titled "Research, investigation, training, and other activities" (42 USC §7403). In the subsection that includes the provision for the continuation of NAPAP, the ecological components mentioned include ecosystems, forests, surface waters, soil, and high-elevation watersheds; ecological effects that could be adverse include changes in surface-water quality, changes in forest and soil conditions, and occurrence of episodic acidification (especially in high-elevation watersheds) 42 USC §7403(j)(3)(E)(iii-v). Additional ecological components and attributes of interest to Congress with respect to adverse effects are named in a preceding Clean Air Act Amendment subsection titled “Ecosystem research” (42 USC §7403(e)), and include “regionally representative and critical ecosystems … crops, biological diversity, wetlands, estuaries, groundwater, other terrestrial systems, and other aquatic systems”; effects named that could be adverse include those that are “short-term and long-term … [show] trends of ecosystem damage …. [are due to] chronic and episodic exposures … [and] multiple environmental stresses.” Also, “sensitive and critically sensitive aquatic and terrestrial resources” are the subject of specific congressional protection to be achieved through the adoption of an acid deposition standard(s) (Appendix B of §404 (42 USC § 7651c) of Title IV of the 1990 Clean Air Act Amendments).

Nowhere in the Clean Air Act Amendments, or associated case law, is the specific type of damage or injury that would constitute an adverse ecological effect specified. Other environmental statutes, however, deal with similar concepts. The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) assigns liability for damage to natural resources from releases of hazardous substances—a broad concept encompassing adverse ecological effects. The term *damages* is defined as “injury or loss of natural resources.” Natural resources are “land, fish, wildlife, biota, air, water, groundwater, drinking water supplies, and other such resources” 42 USC §9601(6,16). The regulations delineating how natural resource damage assessments may be carried out for CERCLA (and also the Clean Water Act (CWA)), are at 43 CFR §11.10 *et seq.*, and define *injury* as:

> a measurable adverse change, either long or short term, in the chemical or physical quality or the viability of a natural resource resulting either directly or indirectly from exposure to … a hazardous substance, or … to a product of reactions resulting from … a hazardous substance (43 CFR §11.14(v)).

There are, in turn, detailed injury definitions applicable to specific resources. Portions of these definitions potentially relevant to ecological effects of acid deposition are at 43 CFR §11.62 and include:

> (e) Geologic resources. An injury … has resulted … if one or more of the following changes … is measured:
>
> > (4) Concentrations of substances sufficient to decrease the water holding capacity such that plant, microbial, or invertebrate populations are affected;
> >
> > (5) Concentrations of substances sufficient to impede soil microbial respiration to an extent that plant and microbial growth have been inhibited;
> >
> > (6) Concentrations in the soil of substances sufficient to inhibit mineralization resulting from a reduction in soil microbial populations;
> >
> > (7) Concentrations of substances sufficient to restrict the ability to access, develop, or use mineral resources within or beneath the geologic resources
> >
> > (9) Concentrations in the soil of substances sufficient to cause a toxic response to soil invertebrates;
> >
> > (10) Concentrations in the soil of substances sufficient to cause a phytotoxic response, such as retardation of plant growth.
>
> (f) Biological resources. (1) An injury … has resulted … if concentration of the substance is sufficient to:
>
> > (i) Cause the biological resource [fish and wildlife and other biota] or its offspring to have undergone at least one of the following adverse changes in viability: death, disease, behavioral abnormalities, cancer, genetic mutations, physiological malfunctions (including malfunctions in reproduction), or physical deformations.

Since natural resources are ecological components, and the injuries are adverse effects, these definitions give a further indication of adverse ecological effects that lie within the intent of Congress within the environmental statutes of CERCLA and the CWA.

Incorporating the content and concepts above, the adverse ecological effects of acid deposition that could lie within the scope of this NAPAP report are those effects that cause—

injury, damage, or deterioration

consisting of

a measurable adverse change, either long or short term, in the chemical or physical quality or the viability of

ecosystems (sometimes causing trends), regionally representative ecosystems, critical ecosystems, other terrestrial systems, other aquatic systems, sensitive and critically sensitive aquatic and terrestrial resources, forests, surface waters, wetlands, estuaries, groundwater, high elevation watersheds, soil, crops, biological diversity, land, fish, wildlife, biota, air, water, drinking water supplies, and other such resources;

due to

occurrence of episodic and chronic exposures, short- and long-term exposure, multiple environmental stresses; and resulting either directly or indirectly from exposure to acid deposition, or exposure to a product of reactions resulting from acid deposition;

and including for geological resources

decreases in the water holding capacity such that plant, microbial, or invertebrate populations are affected; impedance of soil microbial respiration to an extent that plant and microbial growth have been inhibited; inhibition of mineralization resulting from a reduction in soil microbial populations; restrictions in the ability to access, develop, or use mineral resources within or beneath the geologic resources; toxic responses to soil invertebrates; and phytotoxic responses, such as retardation of plant growth;

and including for biological resources

changes sufficient to cause the biological resource or its offspring to have undergone at least one of the following adverse changes in viability: death, disease, behavioral abnormalities, cancer, genetic mutations, physiological malfunctions (including malfunctions in reproduction), or physical deformations.

From this detailed, descriptive, lengthy, and sometimes redundant definition, the working definition of *adverse ecological effects* in the text was derived.